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DATING RAISED BOGS: NEW ASPECTS OF AMS ^{14}C WIGGLE MATCHING, A RESERVOIR EFFECT AND CLIMATIC CHANGE

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Abstract — High resolution AMS dating of Holocene raised bog deposits (Engbertsdijksvenen, The Netherlands) shows natural ^{14}C variations (wiggles) which can be matched with the dendrochronological calibration curve. Comparison of our results with other, conventionally dated peat cores and the $\Delta^{14}C$ record shows an unexpected and as yet unreported reservoir effect, and a marked and sudden wetting of the bog surfaces coinciding with the advent of a Spörer-type solar minimum (the Homeric minimum). The potential of AMS dating to vastly improve the accuracy of Holocene chronologies is demonstrated.

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Conventional ^{14}C dating and calibration (Van der Plicht, 1993) are widely used to estimate ages of Holocene palaeoenvironments. However, in dealing with rapid changes like century-scale climate change, the large (>50 years) and irregular probability distributions of individual calibrated ^{14}C-dates hamper chronological correlation. In an earlier paper we envisaged the possibility of applying AMS 'wiggle matching' for obtaining a better ^{14}C age determination of organic deposits (Van Geel and Mook, 1989). Wiggles in the ^{14}C calibration curve are caused by a varying atmospheric ^{14}C activity in the course of time, yielding short-term variations with a magnitude of 1 to 2% (equivalent to apparent ages of around 100 to 200 years) over periods of a few hundred years. This pattern of ^{14}C wiggles may be recognised in all time series derived from atmospheric carbon dioxide, such as treerings (Stuiver *et al.*, 1993) and peat deposits (Clymo *et al.*, 1990).

For treerings, wiggle matching is more or less routine since the abscissas of the calibration curve as well as the curve to be matched indicate successive ring years (Pearson, 1986). For a series of ^{14}C ages from a peat profile however, sampling depth (or a similar parameter) is plotted on the x-axis. The depths of the dated samples are related to real time by the rate of peat accumulation which is unknown. Part of the computerised fitting process (Van der Plicht, 1993), therefore, is a uniform 'stretching' of the unknown abscissa in order to obtain the same slope for both curves.

The site selected for this study is the Engbertsdijksvenen raised bog in the eastern part of The Netherlands, which has been investigated before (Van Geel, 1978; Dupont and Brenninkmeijer, 1984). For ^{14}C analysis, selected above-ground plant remains from one peat core (ENG XIV; 52°28' N/6°39' E) were pre-treated according to Mook and Streurman (1983). They were combusted to carbon dioxide which was then purified and reduced to graphite. The final ^{14}C measurement was performed with the new Groningen AMS system (Mous *et al.*, 1994, 1995). Dates were corrected for isotope fractionation to $\delta^{13}C$ = -25‰. The standard deviations are <0.5%. The results are shown in Fig. 1a.

The dates obtained on 99–100% pure *Sphagnum* (peat moss) were used to match the ENG XIV sample series to the tree–ring calibration curve (Stuiver *et al.*, 1993) with the wiggle matching option of the Groningen radiocarbon calibration program (Cal120). This option calculates, on the basis of a number of ^{14}C dates and a substitute time scale (for which we used sample depth), a goodness of fit parameter. Analogous to Pearson (1986), this represents the residual sum of squares, but in our approach divided by the number of dates N and its root taken, yielding a standard deviation s. A minimum s can be obtained in Cal120 by manually shifting the peat ^{14}C series in calendar time and increasing or decreasing its total calendar age range.

In Fig. 1a we can observe that pure *Sphagnum* dates are in good agreement with the ^{14}C dates of the calibration curve. A charcoal sample from 96.8 cm depth yielded a date ca. 400 ^{14}C years too old. Part of it probably originated from forest fires in the surroundings of the bog. More striking however, samples containing 2–4%

very fine Ericaceae rootlets (mostly from *Calluna vulgaris*) often yield ^{14}C ages 100–150 years too old. (These samples had been cleaned under a binocular microscope, removing from the *Sphagnum* all other botanical remains except the thousands of tiny rootlet fragments because that was considered too time intensive.) The ^{14}C results were quite unexpected, contradicting the general experience from ^{14}C-dating that rootlet samples are too young, the roots being of a more recent age than the level penetrated.

We compared this result with four raised bog sites published previously (Fig. 1, Table 1), of which many bulk samples have been dated conventionally (Van Geel, 1978 and unpublished data; Dupont and Brenninkmeijer, 1984; Aaby and Tauber, 1975; Küster, 1988). Applying the same procedure as for the ENG XIV AMS ^{14}C series, and again assuming constant peat accumulation rates, we observed that during wiggle matching their ^{14}C dates tended to 'float' above the calibration curve, especially in the range of the 750–400 cal. years B.C. (cal: calendar years) *Hallstatt*-plateau (Fig. 2). It seems that the sites all accurately reproduce the ^{14}C variations, but are shifted to higher ^{14}C ages compared to the calibration curve (Fig. 1b–e). This would mean that the carbon source for the raised bog plants was different from atmospheric CO_2, yielding apparent ages for the plants. This phenomenon is known as a 'reservoir effect' (Stuiver and Pollach, 1977). Other examples are the apparent age of surface ocean water (Stuiver and Braziunas, 1993), caused by the admixture of relatively old deep ocean water, and also of freshwater and related vegetations caused by the uptake of fossil carbonates (Olsson and Florin, 1980; MacDonald *et al.*, 1991).

To evaluate the possibility of a reservoir effect statistically, the wiggle matching option of Cal120 was extended to allow the user shifting the dates vertically as well. On the assumptions of constant (but unknown) peat accumulation rates and a constant (and unknown) ^{14}C reservoir age throughout each peat section, a minimum s could be determined for each peat section, giving both reservoir age and accumulation rate for the best fit (Table 1).

We tested whether the assumption of a reservoir age for the peat bulk ^{14}C samples really improved the goodness of fit. The null hypothesis is:

H_0: constant accumulation rate and no reservoir effect, and the alternative hypothesis:

H_1: constant accumulation rate and a constant reservoir effect

As test-statistic we used: $F_s = s_0^2/s_r^2$, which is assumed to be F-distributed (Sokal and Rohlf, 1981). s_0^2 is the residual variance without, and s_r^2 is the residual variance with a correction for the assumed reservoir effect. Under the null hypothesis F_s would approach 1, as s_0^2 and s_r^2 would be realisations of the same population. We used a one-tailed test, because our alternative hypothesis predicts a decline in s^2 when we correct for a reservoir effect. The results of the F-test are summarised in Table 2. When corrected for a reservoir effect, the fit is significantly better in two cases, Draved Mose and Haslacher See, while Engbertsdijksvenen VII is only just significant. The F-value for Engbertsdijksvenen I was not significant. In summary, in three out of four cases the assumption of a reservoir effect in the peat deposits significantly reduces s^2 after wiggle matching, and H_0 should be rejected.

The statistical results must be viewed in the light of the fact that the ^{14}C data ranges were selected because they could be matched successfully to the 800–400 cal. years B.C. plateau of the calibration curve, especially if a reservoir effect was assumed. This may influence the significance of the results positively. However, though peat accumulation rate changes could always be invoked to reject our proposition, we believe that the strong analogy of the ^{14}C patterns of the conventionally dated raised bog sites with the rootlet-contaminated *Sphagnum* samples from ENG XIV strengthens our case for a reservoir effect in raised bog deposits, amounting to 100–250 ^{14}C years. While research is in progress, we mention two possible origins of the effect, based on the fact that all mires emit trace gases to the atmosphere, mostly CO_2 and CH_4:

(1) CO_2 as such cannot explain the reservoir effect. It is mainly produced in the upper part of the peat column (the acrotelm: Ingram, 1978), and we estimate its maximum apparent age to be 200–500 ^{14}C years. As samples with only 2–4% rootlets have apparent ages of 100–150 ^{14}C years (Fig. 1a), a carbon source with an apparent age of millennia should be responsible.

This can be shown with the 92.9 and 75.8 cm samples (Fig. 1a). Assuming that the rootlets or their contents are the actual cause of the reservoir effect, and that their contribution to total sample carbon equals their volumetric share as estimated by eye with a binocular microscope (!), we can estimate their age with a formula provided by Mook and Streurman (1983, p. 47) for estimating ages of contaminated ^{14}C samples. While clean *Sphagnum* samples from the 92.9 and 75.8 cm levels produced ^{14}C ages of 2481 ± 42 BP (GrA-645) and 2469 ± 45 BP (GrA-811) respectively, samples containing rootlets (4 and 3%) from the same levels yielded 2594 ± 32 BP (GrA-247/258) and 2601 ± 19 BP (GrA-246/256). This leads to age estimates for the rootlets (and their contents) of 5932 and 8764 BP respectively. While these figures are based on eye-estimates of their volume, it should be stressed that only the order of magnitude is indicated.

Carbon causing a reservoir effect this size can be provided by CH_4, produced by bacteria in the lower, permanently anaerobic peat layer (the catotelm: Ingram, 1978). On its way to the surface, part of it is oxidised by methane-consuming bacteria near the catotelm/acrotelm-boundary (Shotyk, 1989), forming a distinct source of very old CO_2 in the root zone. This CO_2 does not dominate above-ground assimilation, but can be fixed by mycorrhizal fungi associated with the living roots. Ericoid mycorrhizal fungi are likely to fix a variety of carbon compounds—including CO and CO_2—(Allen, 1991) and may also transport carbon to their host (Harley and Smith, 1983).

However, though we are unable presently to exclude this mechanism as the cause of the reservoir ages, it seems dubious. If this mechanism would be the main

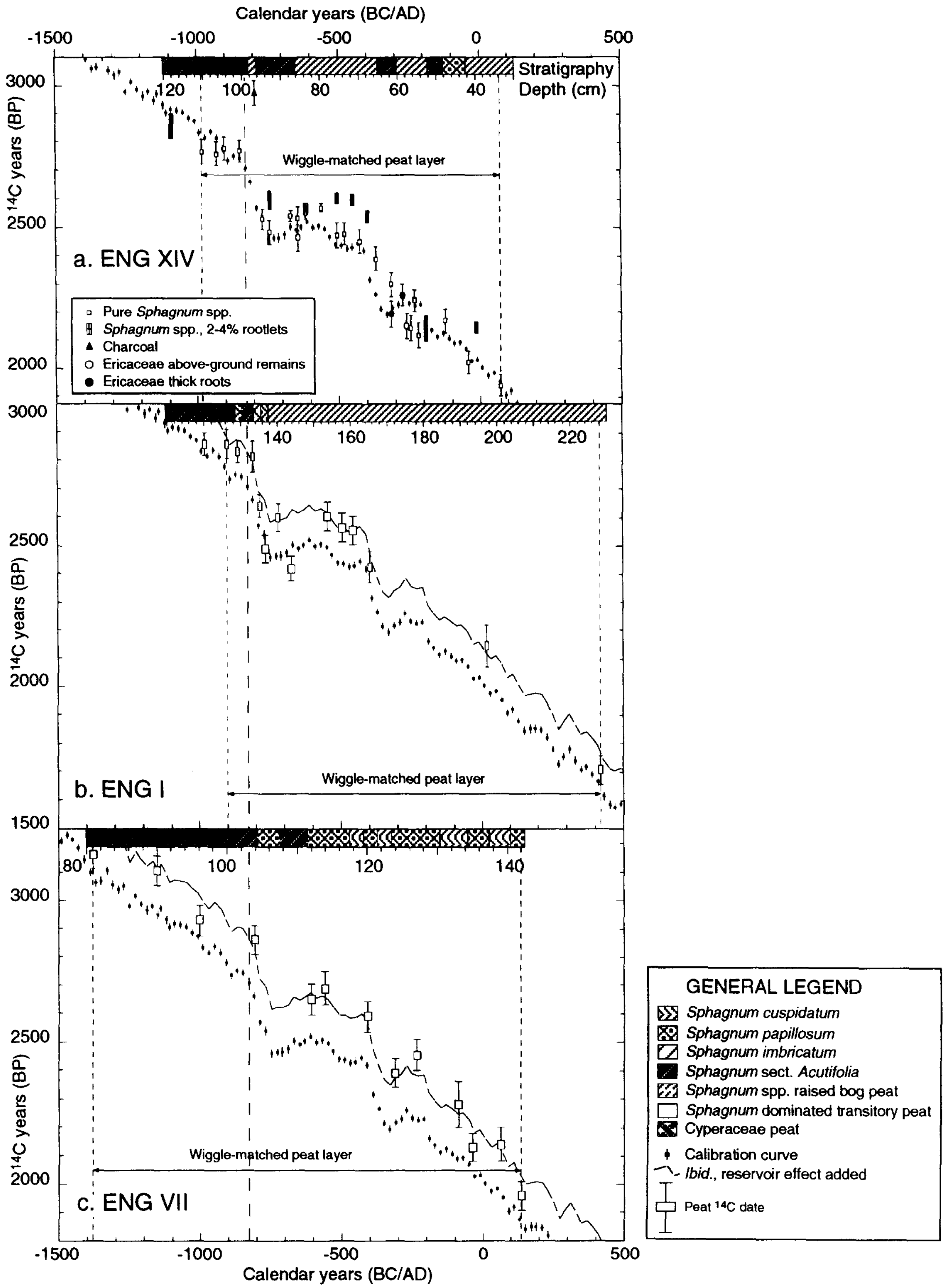

FIG. 1. Five wiggle-matched raised bog cores: (a–c) Engbertsdijksvenen (The Netherlands): (a) XIV (this study), (b) I (Van Geel, 1978 and unpublished data), and (c) VII (Dupont and Brenninkmeijer, 1984).

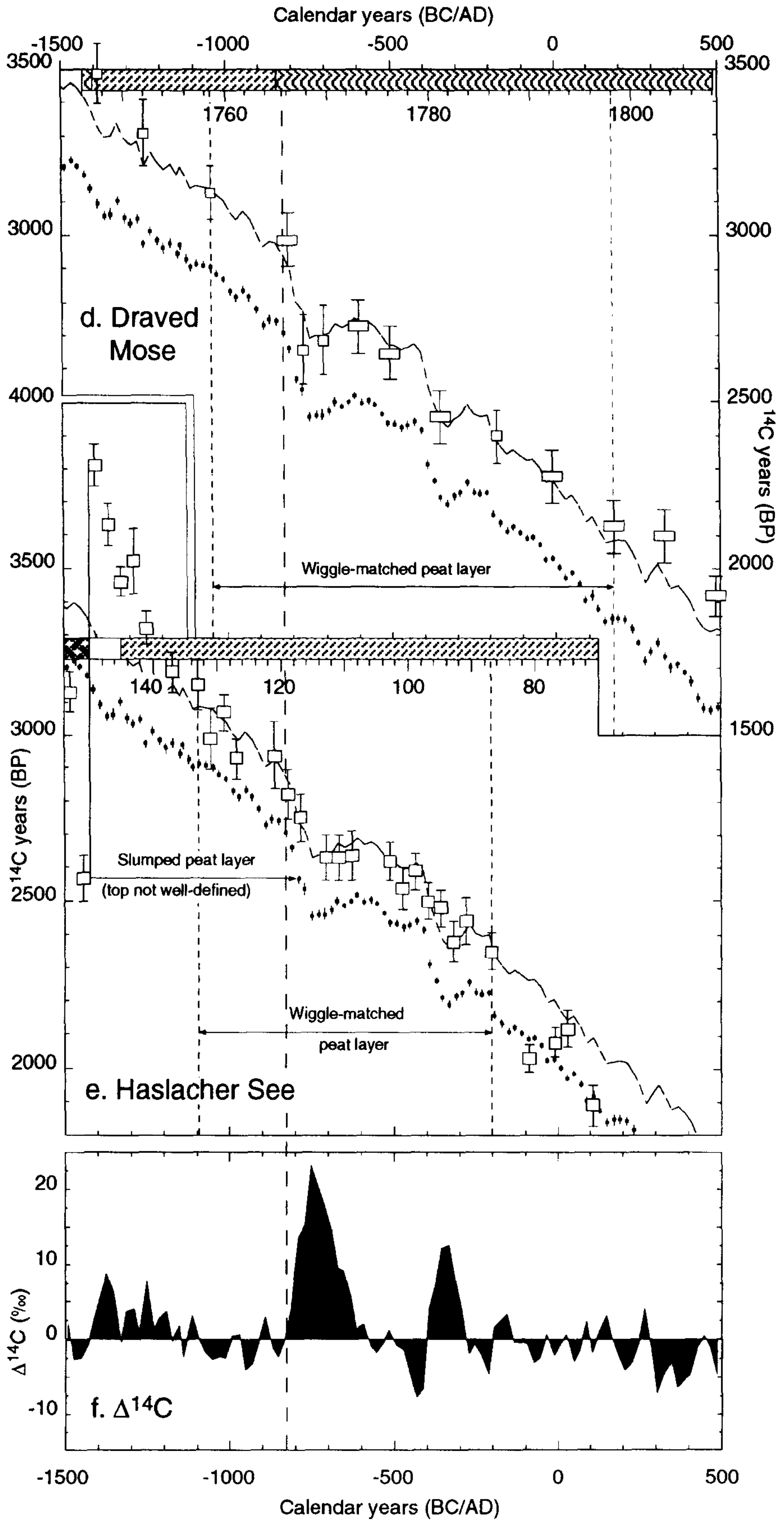

FIG. 1. (d) Draved Mose (Aaby and Tauber, 1975; Denmark); (e) Haslacher See (Küster, 1988; Germany). The uncalibrated radiocarbon ages are plotted against time assuming constant accumulation rates and constant reservoir ages (cf. Table 1). Note in each figure the double horizontal axis: at the bottom, calendar years (calibration curve) and at the top, depth (peat): outside the wiggle-matched range demarcated by short dashes, peat accumulation rates are considered to be different and only their depth scales correct. The distances between the original and upward displaced calibration curves indicate the reservoir effects. The solution for minimal $s(=s_r)$ is shown. (f) Residual Δ^{14}C after subtracting a sinus corresponding to geomagnetic variation (Damon, 1989). Long vertical dashes indicate the start of the Homeric minimum 830 B.C.

TABLE 1. Data from the wiggle-matched raised bog cores, corresponding with Fig. 1. The wiggle-matched peat layer is indicated in cm and calendar years (−: cal. years B.C.; +: cal. years A.D.); Reservoir effect (BP): mean apparent age of peat samples, determined by wiggle matching. The composition of the 'wet peat' varies per site (ENG XIV–VII: *Sphagnum papillosum* and *S. imbricatum*; Draved Mose: *S. cuspidatum*). 0.5d is the dating error estimate caused by sample thickness d (mostly 1963cm), only part of the (undeterminable) total error. Calibrated ages of the original dates are shown for comparison

Site	Wiggle-matched peat layer	Depth (cm)	Age (calBC/AD)	Reservoir effect (BP)	Accumulation rate rate (y/cm)	Start wet peat Depth (cm)	Age (wiggle-matched) (± 0.5 d; calBC)	Age Calibrated ^{14}C age (calBC/AD)†
	top	33.9	+72					
1. Engbertsdijksvenen XIV				0	13.8	98.3	815 (±3.4)	
	bottom	110.4	−982					
	top	228	+417					
2. Engbertsdijksvenen I				117	12.9	129	862 (±6.5)	1116–860 cal. years B.C.
	bottom	126	−901					(2835 ± 40 BP)
	top	142	+137					
3. Engbertsdijks venen VII*				149	24.9	105	784 (±12.5)	1200–860 cal. years B.C.
	bottom	81	−1382					(2860 ± 50 BP)
	top	1798	+174					
4. Draved Mose*				237	30.9	1765	848 (±15.5)	1408–996 cal. years B.C.
	bottom	1758.5	−1049					(2990 ± 80 BP)
	top	87	−200					
5. Haslacher See				163	19.4			
	bottom	133	−1094					

*The Eng VII and Draved Mose cores, because one sample contains more than 20 years, have been matched to a calibration curve which was fully smoothed according to the Rheinsch algorithm.

†The calibrated radiocarbon ages have a non-Gaussian probability distribution, and we only quote the extreme limits of the 95.4%-confidence intervals. The uncalibrated ^{14}C age is given between brackets. The samples were taken within 1 cm of the stratigraphical transition.

cause of an almost omnipresent reservoir effect, almost any heather currently growing on a bog would have 'subfossil' mycorrhizal roots. However, AMS measurements of rootlets of living *Calluna vulgaris* and *Erica tetralix*, carried out to test this hypothesis, yielded modern ages (unpublished data).

(2) Alternatively the rootlets may obtain their apparent ages after death, also by fungi fixing CH_4-derived C. Actually the methane-derived C is not necessarily sequestered in the rootlet tissue itself, but could merely be the exclusive carbon source for specialised fungi. The proposed mechanism is that they colonise ericaceous tissue, and still are inside the rootlets during ^{14}C sample preparation. The presence of large quantities of (mostly taxonomically unknown) fungi in fossilised *Calluna* roots has been demonstrated (Van Geel, 1978). Whether this can explain the reservoir effect will be tested with future AMS ^{14}C measurements of fungal remains.

Linked to a calendar time scale by wiggle matching (Table 1, Fig. 1), the bog stratigraphy can be compared with other Holocene climate-related time series. Moreover, the accurate timescales constructed allow direct comparison with the atmospheric $\Delta^{14}C$-record as observed in treerings, considered to be a proxy record of solar activity (Fig. 1f). $\Delta^{14}C$ is the relative deviation of the measured standard activity, after correction for isotope fractionation and radioactive decay (Stuiver and Pollach, 1977).

A relation between solar activity and climate is not generally accepted (Stuiver *et al.*, 1991; Kerr, 1995). Wigley and Kelly (1990) identified low dating accuracy as one problem in chronologically correlating glacier fluctuations with the $\Delta^{14}C$ record, pointing to a general problem for many palaeorecords. The $\Delta^{14}C$ pattern however, is very similar to that of Holocene climate records (Magny, 1993; Röthlisberger, 1986), which are also highly correlated amongst themselves, suggesting solar variation as the common cause for both climate and isotope variations. Though a proper mechanism still has to be established (Kerr, 1995), the $\Delta^{14}C$ record may be called an empirical indicator of Holocene palaeoclimates, with periods of low solar activity coinciding with high $\Delta^{14}C$-

TABLE 2. Results of *F*-test for four wiggle-matched raised bog cores: s_0^2: residual variance after wiggle matching not assuming reservoir ages; s_r^2: residual variance after wiggle matching assuming reservoir ages (cf. Table 1). For explanation see text

Site	Number of dates	s_0^2	s_r^2	s_0^2/s_r^2	$F_{0.05}$	Probability (1-tailed test)
1. Engbertsdijksvenen I	13	5935.16	4444.89	1.34	2.69	
2. Engbertsdijksvenen VII	13	7430.44	2760.45	2.692	2.69	$p < 5\%$
3. Draved Mose	10	9607.92	1825.85	5.26	3.18	$p < 2.5\%$
4. Haslacher See	18	4946.31	1793.52	2.76	2.28	$p < 2.5\%$

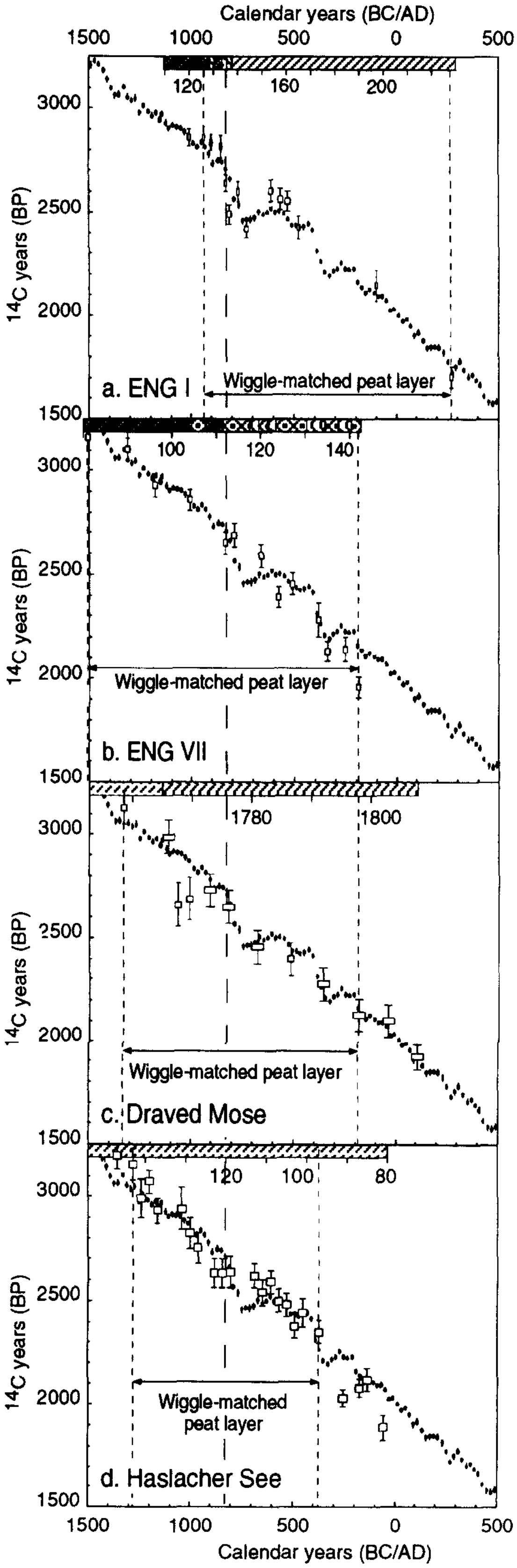

FIG. 2. Four wiggle-matched raised bog cores: (a) ENG I; (b) ENG VII; (c) Draved Mose; (d) Haslacher See. ^{14}C ages are plotted like in Fig. 1, but assuming no reservoir ages. The solution for minimal $s(=s_0)$ is shown (cf. Table 2).

values and a cool/wet climate (Damon, 1989; Davis *et al.*, 1992) indicated for instance by lake level records (Magny, 1993) and glacier advances world-wide (Röthlisberger, 1986).

Living raised bogs are lens-shaped, their centre rising above the surroundings. They depend for nutrients and moisture on atmospheric precipitation and thus are sensitive to climatic change (Aaby, 1976). Analogous to lake systems (Magny, 1993), decreasing precipitation, or rising temperatures causing increased evapotranspiration, would effect a fall in bog water level, and vice versa. Drying out or wetting of the bog surface is reflected in the species composition and degree of humification of the peat (Aaby, 1976; Van Geel, 1978). Visible changes from more humified to less humified peat are termed Recurrence Surfaces (Granlund, 1932), a special case being the *Grenzhorizont* dated to ca. 1000–500 years B.C. in many Northwest European raised bogs and thought to mark increased climatic wetness (Overbeck, 1975).

In the Engbertsdijksvenen cores, this transition occurs at ca. 862–784 cal. years B.C., coinciding with the rise of the wetter growing *Sphagnum papillosum* and *S. imbricatum* (Van Geel, 1978; Overbeck, 1975). In Draved Mose, the hygrophilous *Sphagnum cuspidatum* becomes dominant at ca. 848 cal. years B.C., when the moisture indicator *Amphitrema flavum* also shows maximal values (Aaby and Tauber, 1975; Aaby, 1976). In the Haslacher See, the ^{14}C pattern evidences a dramatic event (Fig. 1e). While the youngest ^{14}C age of the Cyperaceae peat is shown as 2570 ± 70 BP (ca. 800 cal. years B.C.), the *Sphagnum* peat layer on top (150–100 cm) started accumulating at 3810 ± 65 BP (2458–2038 cal. years B.C., 95.4% confidence interval). The same period is represented twice because an already formed *Sphagnum* peat layer slumped onto the Cyperaceae peat around 800 cal. years B.C. (Küster, 1988), which was probably triggered by increased precipitation.

An individual raised bog site can react to climate change with a time lag. Climatic cooling/wetting will raise the water table first in the central, flatter parts of the bog (due to the lower gradient in hydraulic potential; Ingram, 1982), and only later in the marginal zones. Closest to the centre in the Engbertsdijksvenen bog area is core ENG I, indeed the first study site colonised by *Sphagnum papillosum* and *S. imbricatum*, at the same moment as *Sphagnum cuspidatum* conquers the Draved Mose site (Table 1). The related maximum in $\Delta^{14}C$, the so-called 'Homeric minimum' (Landscheidt, 1987) starts at 830 ± 10 cal. years B.C. (Stuiver *et al.*, 1993) (Fig. 1f), 20–30 years later. This equals the time atmospheric ^{14}C concentration lags behind production rates (Damon, 1989; Eddy, 1988).

Only very high dating accuracy produced by AMS technology and wiggle matching, makes it possible to correlate these features properly. The reservoir effect described has the same order of magnitude as the signal to be understood. The data presented show that using calibrated bulk dates from raised bog deposits often leads to correlations that are ambivalent, or even opposed to reality. While wiggle matching, correcting for the reservoir effect, puts the transition to a wetter climate firmly in a period of rapidly rising atmospheric ^{14}C-values (Fig. 1), calibrated single ^{14}C-dates would yield the exact opposite: the change is suggested at 1408–860 cal. years B.C. (cf. Table 1), coinciding with falling $\Delta^{14}C$. The same holds for wiggle matching if a reservoir effect is not anticipated (Fig. 2).

In conclusion the raised bogs studied show climatic wetting coinciding with the start of the Homeric $\Delta^{14}C$ anomaly, without an observable time lag. This strongly suggests a common cause, viz. changing solar activity. We conclude that for proper ^{14}C dating of peat deposits (1) pure *Sphagnum* or other above-ground plant remains should be used, which is now a real possibility owing to the advance of AMS, and (2) wiggle-matching increases dating accuracy. If neither is done, unrecognised dating errors up to 500 years may arise (Table 1), hampering all further research after the chronology and effects of climatic change, a climate-^{14}C link included.

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